EXHIBIT 26

GraphicsNet '95: Integrated Voice, Video, Graphics and Data Network Using Asynchronous Transfer Mode (ATM)

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Abstract
Every year demonstrations at the SIGGRAPH conference push the envelope in state-of-the-art graphics. In 1995, SIGGRAPH also pushed the envelope in networking by deploying a conference-wide, production ATM network. GraphicsNet, the conference network, consisted of 400 Ethernet-over-ATM connections and 100 directly attached ATM devices. GraphicsNet was one of the largest ATM backbone networks deployed to date. Using the latest hardware and software available, GraphicsNet provided a switched internetwork to met the requirements of the demonstrations and exhibits at SIGGRAPH 95.

SIGGRAPH 95, held at the Los Angeles Convention Center, required a network that would integrate voice, video, graphics and data all on one networking infrastructure. The GraphicsNet Team was formed to provide an advanced multi-gigabit-per-second network for the conference. In order to meet the requirements of the participants at SIGGRAPH 95, the combined efforts of FORE Systems, Inc., Hewlett Packard Labs and Pacific Bell were necessary to design and build a state-of-the-art network based on the evolving networking paradigm of switched internetworks. GraphicsNet's Asynchronous Transfer Mode (ATM) based network provided the facility for remote collaboration at SIGGRAPH 95 for exhibitors, Interactive Communities, Interactive Entertainment, Digital Demo and many other locations within the Los Angeles Convention Center and throughout the world.

The GraphicsNet'95 sub-committee wanted to push the envelope by pioneering two major applications utilizing the bandwidth available on the ATM network, the GraphicsNet access "kiosks" and the Digital Demo. The GraphicsNet access kiosks brought a VRML representation of SIGGRAPH 95 and full motion video to the attendees through kiosks located in the lobbies. Digital Demo provided participants a hands-on environment to learn about the digital studio process by building a digital studio at the LA Convention Center.

GraphicsNet illustrates the evolution of social interaction by supplying high-bandwidth WAN connectivity to SIGGRAPH 95's diverse group of collaborators in the LA area, across North America, and around the world. Due to the nature of high-speed WAN's users were unaware of when they were accessing data on the Local Area Network (LAN) or on the Wide Area Network (WAN).

Overview

The primary goal of GraphicsNet was to provide high performance internetworking services for the SIGGRAPH 95 Convention at the Los Angeles Convention Center. User requirements included switched Ethernet, ATM and High-Performance Parallel Interface (HiPPI) for local area connections. Wide area connections included ISDN and ATM. Another primary requirement was high speed Internet connectivity. Many of the participants in SIGGRAPH 95 demonstrations were based on the world wide web. Instead of bringing their servers to the conference, they wanted to be able to connect to them over the Internet. Another requirement for the Internet connection was MBONE broadcasts from any location in the LA Convention Center. A final requirement was remote collaboration over ATM.

The focus on applications at SIGGRAPH 95 placed a demand for very low latency and high bandwidth on the network. It also placed a demand on the network for integrated services to transport full motion video, high resolution graphics, stereo quality audio and data. Building a separate video, voice and data network would have been prohibitively expensive. ATM was chosen as the technology that best met the user requirements of the network.

In addition to building an advanced switched internetwork, the GraphicsNet subcommittee embarked on two projects that would utilize the infrastructure built. The first project, the Digital Demo, demonstrated the digital studio process by giving participants at SIGGRAPH 95 a hands-on look at the process of digital production. This project will become a part of the Applications venue at SIGGRAPH 96. The second project brought the conference out to the public by providing attendees with a detailed 3-D representation of the LA Convention Center and the SIGGRAPH 95 contents. The GraphicsNet access "kiosks" utilized two technologies to provide the users this access in the lobbies of the LA Convention Center, VRML and ATM. VRML provided the user interface and ATM provided the bandwidth necessary for the audio and full motion video to the kiosks and between them. Using the high-speed network, users on the kiosks could view full motion video clips from Digital Demo's video servers.

The network built for SIGGRAPH 95, could have supported a corporation of over 500 people. The planning stage took four months while the execution only took 7 days. Over ten miles of fiber and copper cabling was installed throughout the 1 million square foot LA Convention Center to interconnect the computers used at the conference. PacBell installed an OC-48 SONET ring to service the remote collaboration requirements of SIGGRAPH 95.

Building a network of this size and complexity would normally take millions of dollars and months to install. The GraphicsNet team had the network fully installed and running within 7 days. This included the installation and configuration of all networking hardware, running the copper and fiber cable plant, configuration and installing the workstations for compute servers and the GraphicsNet access kiosks, the building of the Digital Demo Studio and helping users troubleshoot their networking problems. It also included installing the facilities for the video applications that ran on the network. All of the networking equipment required to build GraphicsNet'95 was donated.

Building a conference network based on the new networking paradigm of switched internetworks requires skill and expertise that is not widely available. The core team of networking professionals numbered less than 15. The GraphicsNet team consisted of industry experts in the areas of ATM, routing, HiPPI and traditional networking. Along with these experts, the leading companies in the market donated their employees' time and the equipment to make this network a reality.

The result was a stable, high-performance network that supported over 400 Ethernet nodes, 100 ATM connections and 15 HiPPI devices. A single emulated LAN over ATM supported the 400 Ethernet connections. The emulated Ethernet LAN was built with a com-

bination of intelligent Ethernet hubs from Hewlett Packard and Ethernet Switches from LANNET. FORE Systems provided the Ethernet to ATM access devices and the ATM switches. The ATM network was built on the same ATM switches that were used for the Emulated Ethernet and used a variety of ATM network interface cards (NIC) from FORE Systems. Essential Communications provided an ATM-to-HiPPI gateway that provided the data path from HiPPI switches from Essential and the rest of the conference network. Finally, Hewlett Packard donated a Cisco router to interface to the Internet.

An OC-12c (622 Mbps) ATM link provided the backbone connection between the two major sections of the LA Convention Center. This link included OC-12c network modules from FORE Systems and a SONET link from PacBell. Silicon Graphics provided a Power Challenge XL and a Challenge L to serve as video database servers, VRML servers and compute servers. Hewlett Packard provided the workstations and HP OpenView for network management. Sun Microsystems provided several workstations to serve a variety of functions including the MBONE router, DNS server and HTML server. UNAMEIT, provided by Enterprise Systems Management, was used to manage the host name space and the domain name service.

During the 5 days of the conference the Ethernet network experienced hours of average load at 75%. Sections of the Ethernet experienced peak utilization of'94% without performance degradation. The sustained traffic to the Internet was 2.4 Mbps with frequent peaks over 10 Mbps. During heavy usage, the Internet connection averaged 5 Mbps. The OC-12c backbone link sustained traffic loads over 170 Mbps for hours at a time. The traffic mix on the OC-12c link consisted of full motion video, VRML and HTML. In addition to the local services, the OC-12c data link carried MBONE feeds and WWW services to the Internet. Although this did not stress the OC-12c link, it would have been too much for an OC-3c (155 Mbps).

The remote ATM sites all sustained high levels of traffic. The two coast-to-coast video streams used by Eastern Carolina University's Telemedicine application consumed 24 Mbps. MAGIC Gigabit test bed used another 10 Mbps on the DS-3 link to Sprint's ATM network. Monterey Bay Aquarium used the remaining bandwidth on the Sprint ATM link (45 Mbps maximum).

PacBell supplied a second DS-3 ATM network connection. This provided connectivity to the Digital Demo at the LACC with the University of Southern California's Film School, Visual f/x, Warner Brothers and TRW. These participants demonstrated remote collaboration in the digital production cycle. This link continuously ran at 30 Mbps as participants in the Digital Demo viewed and edited video stored at Warner Brothers Studios.

Applications on GraphicsNet

The GraphicsNet team had a vision of providing SIGGRAPH 95 with more than just a network infrastructure. The team wanted to implement a contention-less switched internetwork that would be used to its fullest potential. Therefore the team lead the effort of the GraphicsNet access kiosks and the Digital Demo. To support these two applications and four applications in the Interactive Communities, GraphicsNet partnered with PacBell and Sprint to provide access to their ATM networks.

PacBell's CALREN network provided high-speed access to Warner Brothers, Visual f/x, and USC's Film School from the Digital Demo at SIGGRAPH 95. A collaboration between PacBell and Sprint provided the same high-speed access to Monterey Bay Aquarium, Magic Gigabit Testbed, and Eastern Carolina University.

In addition to the advanced applications the GraphicsNet team delivered standard networking requirements over the ATM infrastructure. Video was sent to the MBONE for more than 5 hours every day of the conference. The servers in the Internet access room were on ATM while all of the xterms and PCs were on Ethernet.

GraphicsNet Access (kiosks)

The GraphicsNet access kiosks were designed to give the participants of SIGGRAPH 95 a way to visually experience the speed and bandwidth of the ATM network. The idea behind the network was to provide participants with a peak into their future corporate networks and the Internet. To do this high bandwidth data paths to the workstations had to be supplied and bandwidth hungry applications had to be used. Three applications met these requirements: VRML, full motion video, and video servers. These applications all provide a visual interface to the user while using the high-speed network to transport data.

SGI donated 18 Indy workstations to serve as the GraphicsNet access kiosks. These computers had level 2 caches in them and GIA-200 ATM Cards donated by FORE Systems. ATM enabled the workstations to "see" the other kiosks by displaying the output of a camera on a remote kiosk on the local display.

VRML Representation of LACC

Silicon Graphics built a 3-D VRML based representation of the LA Convention Center from 2-D CAD drawings supplied by LACC. Next, they took the CAD drawings of SIGGRAPH and applied the content of the conference to the 3-D representation of the LA Convention Center. This provided the user with an interactive 3-D fly-through of SIGGRAPH 95. As the user moved down the isles of the virtual exhibit floor the name of the companies in the booths appeared. If they stopped and clicked on the company name, the on-site Web pages describing the activities of that company's booth at SIGGRAPH 95 were displayed.

Figure 1 is a depiction of the top level of this representation. This is a high-level view of the entire Los Angeles Convention Center. The arrows arranged around the squares show the locations of the kiosks. The large hall on the left is the South Hall where Interactive Communities and the Exhibits are located. The rectangle in the center is the concourse and the large square on the right is the West Hall.

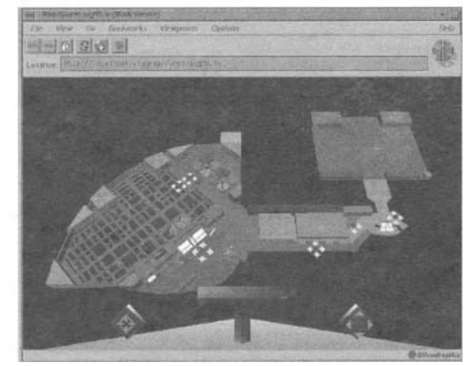

Figure 1: VRML Representation of Los Angeles Convention Center

Using the standard VRML controls located at the bottom of the screen the user can move into an area. The data was transferred over the ATM network to the GraphicsNet access kiosk from the VRML server. Figure 2 is what the user saw when a fully represented booth was zoomed into. In this figure we have "flown" into one of the Silicon Graphics Booths. We can see the demonstration stations SGI had setup for the exhibits. In the live model, selecting the demo area would result in a connection to the *siggraph.org* Web server on the ATM network that would serve the HTML page on that

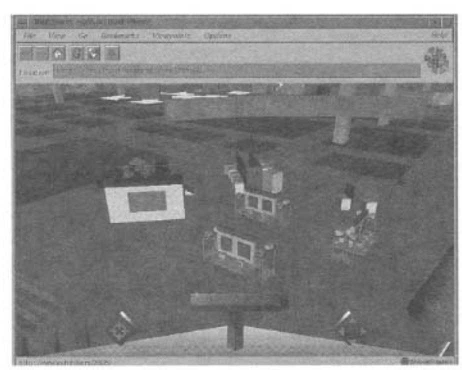

Figure 2: VRML Representation of the Silicon Graphics Booth

demonstration. Selecting a different area in the booth would download the HTML page for that particular demonstration.

This technology allowed the user to not only visually locate the exhibitor's booth, but also find out what demonstrations that exhibitor was performing and their locations. Ideally this model would be available several weeks before the conference allowing participants to plan their route through the exhibit hall.

Wizards World gave users a chance to experience shared Web space. The VRML shared environment included all of the GraphicsNet access kiosks. A user could "see" and talk to the avatars of the other users in the shared world. The volume each kiosk user would hear was modulated based on the distance of their avatar from the speaking avatar in the shared environment. Designers of the VRML software were able to watch novice and expert users using their application. This gave them immediate feedback on the usability of the software. Based on their observations at SIGGRAPH 95, SGI engineers modified several aspects of WebSpace to present a more intuitive interface to the user.

SGI donated two servers to provide VRML and video services. A Power Challenge XL running IRIX 6.0 was located in the GraphicsNet booth in the South hall. FORE Systems installed three OC-3c ATM cards into the Power Challenge providing a 465 Mbps data pipe to the users at the conference. This server provided content to the GraphicsNet access kiosks and served as a Cinebase (donated by Visual f/x) data server for exhibitors and the Digital Demo. The Challenge L in the Silicon Graphics booth serviced demonstrations in the booth as well as some of the content to the GraphicsNet access Kiosks.

3-D Fly-through of LACC

Brain Blau of Autodesk produced a 3-D reproduction of the LA Convention Center. Sony Imageworks produced a 7 minute video tape that contained a complete fly-through of the LA Convention Center. This was shown in the Video Greenhouse and was also accessible from the GraphicsNet access kiosks over the ATM network at a full 30 frames per second. Figure 3 is one frame from the fly-through. This particular frame is a view of the South Lobby.

The 3D model of the LA Convention Center was used by the SIGGRAPH 95 Conference Committee to enhance design implementation of the conference environment. The model was build from AutoCAD plan drawings and construction bluelines. The mass modeling was then created using

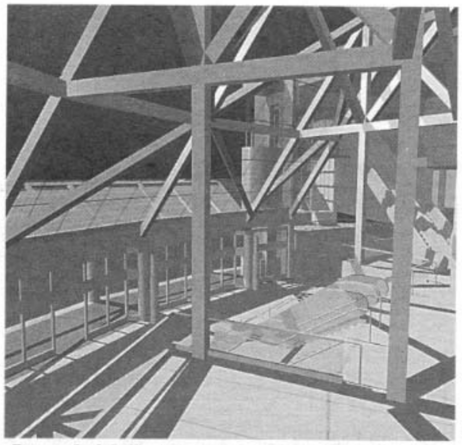

Figure 3: *3-D Fly-through Frame of LA Convention Center.*

AutoCAD and 3D Studio with assembly, refinements and final renderings generated in 3D Studio R4.

Cinebase

Cinebase, the third application on the GraphicsNet access kiosks, provided users a look into the technology of a simplified user interface for very large multimedia databases. From kiosks located throughout the LA Convention Center users could access movie clips and high resolution graphics from a number of databases located on the ATM network. The speed provided by the ATM network allowed users to play back the video at 30 frames per second continuously over the network.

Databases were located on SGI servers in the Digital Demo room and the GraphicsNet booth demonstrating the virtual environment that ATM can create. Users in the Digital Demo accessed video databases from Visual f/x over the PacBell ATM network. From the kiosk location in the lobby, the user would select one of the databases. If the database at Visual f/x was selected the images would enter the network in the Visual f/x corporate headquarters building. From this building they would move onto PacBell's CALREN network which was directly connected to GraphicsNet by a DS-3 ATM link. Once the database link was created from the Visual f/x headquarters building to the LA Convention Center, it would be delivered to the kiosk over the local ATM network. The low latency and high bandwidth provided by ATM made it impossible for the user to tell where the database was located.

GraphicsNet Digital Demo

GraphicsNet Digital Demo, a fully functional digital production studio, demonstrated a networked interactive environment showcasing hardware and software designed specifically for digital creation, distribution, and storage of film, video, photographic, and multimedia content. The studio was installed at the LA Convention Center to provide participants with a hands-on environment to explore the components used to produce and manage film and video assets.

The Digital Studio is designed to encourage human interaction through individual Silicon Graphics workstations linked to local and wide area networks over the GraphicsNet ATM network. Attendees experienced first-hand the process of producing entertainment assets, including content creation, distribution, and archiving.

Ciprico, EMASS, FORE Systems, Silicon Graphics, Pacific Bell, Viewgraphics and Visual f/x provided equipment and experts to put equipment into the hands of the participants. Film, graphics and video clips were retrieved remotely from the University of California (USC) Film School, Warner Brothers and Visual f/x. Due to the high-speed data rates achieved by the ATM connection to PacBell's ATM network, CALREN, users were unable to determine what data was local and which was remote.

Each of the four stages of the digital process were demonstrated. These stages are content creation, digital dailies, distribution, and archival/storage. An SGI Challenge L provided local databases to the 5 Indigo II and 3 Indy workstations in the studio.

Content Creation

In this stage, attendees saw the creation of material with the use of Integrated Video running on Silicon Graphics workstations with Ciprico RAID Disk Arrays. As content is created through non-linear editing, the user manages each piece with Cinebase Asset Management Software. The content is then linked to GraphicsNet's ATM and the material is sent to the next level. GraphicsNet Digital Demo utilized three SGI workstations for this stage. One of these workstations was equipped with SGI's Cosmo and Gallileo cards.

Digital Dailies

Interactive access and high resolution display of the content created in stage I was provided by Viewgraphics Viewstore 6000. Viewgraphics provided its Dataview system providing visitors with access to data on D1. The Viewstore 6000 in use at the Digital Demo provided unprecedented speed and quality for motion image analysis.

Distribution

The Distribution stage highlighted the ATM WAN provided by PacBell. Content was stored and retrieved from local servers throughout the LA Convention Center as well

as CALREN, PacBell's ATM Metropolitan LA Network, sites like USC, Warner Brothers and Visual f/x. The key technology in this phase was the combination of Cinebase and ATM. Servers attached to ASX-200BX ATM switches at Visual f/x's corporate offices provided content to the Digital Demo over an ATM network with 45 Mbps of bandwidth available.

Archival and Storage

An EMASS AML/J was used to stored content in Metrum and DLT formats. The use of the equipment was simplified through the user interface of Cinebase. By dragging an icon representation of the content to a tape storage icon, the content was transferred over the ATM network to a robotic tape storage unit.

Interactive Communities on ATM

Interactive Communities had four demonstrations that utilized the features of ATM. Eastern Carolina University ran a medical clinic at SIGGRAPH 95 by bringing the medical doctors to Los Angeles through a video link to North Carolina. The MAGIC Gigabit Testbed demonstrated their terrain mapping program accessing satellite imagery over an ATM network. Monterey Bay Aquarium showed their collaborative networking efforts through their ATM link. The University of California's Film School demonstrated HollyNet throughout the week.

Telemedicine – East Carolina University

Attendees at SIGGRAPH 95 were able to participate in a first of ever coast-to-coast telemedicine clinic sponsored by East Carolina University School of Medicine and its Center for Health Sciences Communications. The clinic was built at the LA Convention Center and tied to the doctors in North Carolina via a nationwide ATM Network. This network carried two streams of audio/video and one of data. Patient records were transferred over the network along with the video to the scheduling nurse and the diagnostic quality video to the MD. Over 100 SIGGRAPH 95 attendees participated in the demonstration by either making appointments in advance over the Internet or as drop-ins. Fifteen different areas of specialization were represented during the 40 hours of physicians' time during the one week conference. Special telemedicine diagnostic tools were available for physicians to hear a patient's heart beat, examine their ears or look at a skin lesion.

ECU is the head-end for the Institutional Channel, a public service channel on the local cable TV system. This channel is typically used to provide continuing medical education programs for the general public. Programs centered around preventative medicine tips

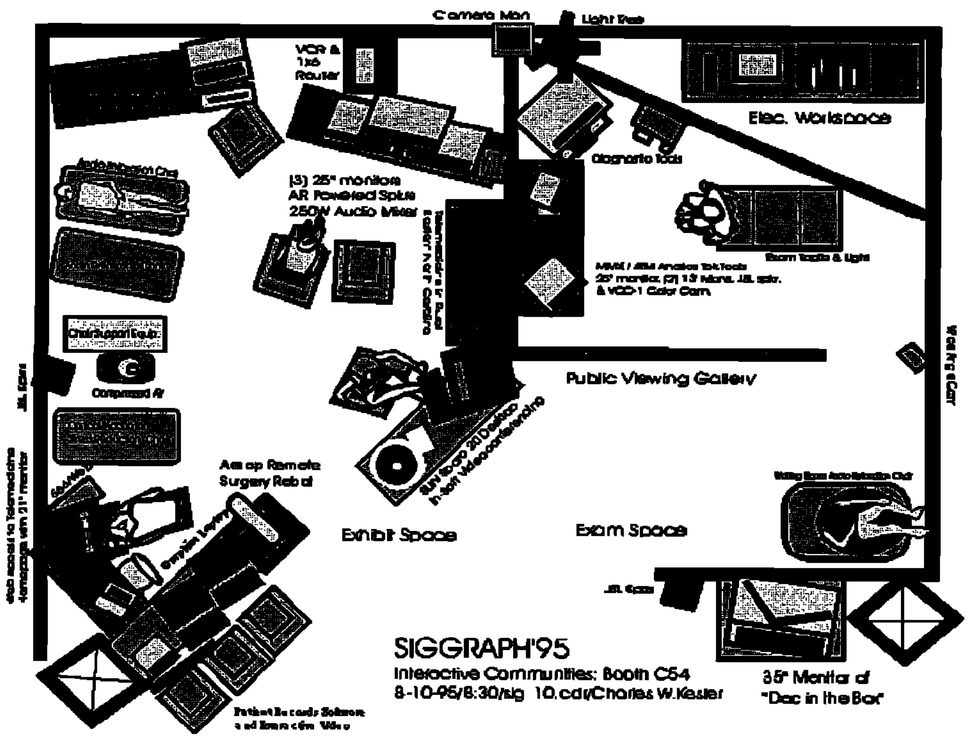

Figure 4: *Telemedicine Booth Layout at SIGGRAPH 95*

for consumers are also sent from ECU to the Cable TV system. Since this system can take ATM video as an input, the "patients" from the Los Angeles Convention Center participated in a live broadcast to 10,000 homes around Eastern Carolina University. A audio/video router system was used to send T1, microwave or ATM video into the cable TV system. To perform this feat three different routers were necessary. A audio/video routers used were from Utah Scientific, Hedco and Iris Technologies.

The telemedicine demonstration would not have been possible without the use of ATM technology. Several hurdles had to be overcome to make this demonstration a reality. High quality full motion video, audio and data, coast-to-coast, were necessary to link the patients with the doctors. This require's an 18 Mbps link for doctor-to-patient communications and a second stream of 5 Mbps for the scheduling workstation, patient-to-nurse. An ATM network had to be installed at ECU in North Carolina. Local access carriers (the local telephone companies) on both ends had to donate a DS-3 link into the facilities. GraphicsNet needed to be built. Most importantly, 40 hours of doctors' time had to be available to advise the patients at SIGGRAPH 95.

Sprint donated bandwidth on their nationwide ATM network to accommodate the video traffic from ECU's telemedicine suites to the examination room in the LA Convention Center. This took over a month of coordination between Bell Atlantic, Pacific Bell, FORE Systems, Sprint and Eastern Carolina University. The video network at Eastern Carolina was already in place as part of their "Doc in the Box" project.

FORE Systems donated equipment and personnel to build the ATM network at ECU. This installation took less than 2 days. During this two day period an ASX-200BX was installed along with an adapter for a Sun Sparcstation. A video to ATM device from STS Technologies was connected to the ASX-200BX and tested. The DS-3 to Sprint's ATM network was also connected and a virtual path was established.

In order to give the users of the network more control, a virtual path was requested from Sprint. This provided ECU with the ability to establish any number of virtual channels over the ATM link without specifically requesting them from Sprint, PacBell and Bell Atlantic. This allowed the GraphicsNet team to run ATM signaling over this virtual path from Los Angeles Convention Center to ECU in North Carolina. This proved that ATM signaling can withstand coast-to-coast delays caused by the speed of light and switching delays imposed by the carrier ATM switches. It allowed the GraphicsNet team to monitor the ATM network at ECU remotely from LA.

Several lessons were learned as a result of this project. One was that the companies carrying the ATM traffic across the country cur-

rently discard cells randomly when congestion occurs. So the end systems need to be able to recover from the errors that occur when all of the data does not make it through. This will change as traffic management schemes developed by the ATM Forum are implemented by switch vendors. In an example of technology surpassing society, it turns out that medical doctors licensed in North Carolina cannot practice medicine in California.

MAGIC Gigabit Test Bed

The MAGIC Gigabit Test Bed group demonstrated TerraVision at SIGGRAPH 95. Attendees were able to view and navigate through high-resolution aerial and satellite imagery. This distributed application allows users to superimpose on the view of the terrain vehicles which will update all viewers in realtime. Three main components are used in this application: an interactive terrain visualization application (TerraVision), a high-speed distributed image storage system (ISS) and a high-speed internetwork to link the computing resources.

GraphicsNet provided a new node on the MAGIC ATM backbone. Access speeds on this network are OC-3c and OC-12c. The backbone trunk speed is 2.4 Gigabits-per-second. Attendees who visited the MAGIC demonstration at SIGGRAPH 95 were unaware that the application they were running was actually distributed throughout the United States.

MAGIC is an ARPA-funded collaboration of the EROS Data Center, Lawrence Berkeley Laboratory, the Minnesota Supercomputer Center, SRI International, the University of Kansas, MITRE, Sprint, USWest, Southwest Bell, Northern Telecom, and Splitrock Telecommunications.

Monterey Bay

Monterey Bay has a regional network connecting K-12 schools, colleges, and universities in Monterey and Santa Cruz counties. The network provides researchers, educators, and students full Internet access and free tools for creating text, hypertext, multimedia, audio, and video documents and productions. Users of this network had high-speed access to GraphicsNet through an ATM link between Monterey and Los Angeles. Most Monterey Bay educators are new to the Internet. The connection to Interactive Communities helped them experience high-speed wide area networking firsthand, allowing them to explore how live interactive graphics could be used in the classroom.

The San Jose Tech Museum of Innovation sent people to SIGGRAPH 95 to demonstrate their half of the Monterey Bay Aquarium to SJTMI BayLink. This application connects scien-

Figure 5: *Jon Bigelow Displays Portable MBONE cart at SIGGRAPH 95*

tists operating a deep robot in Monterey Bay to an auditorium at the aquarium to visitors at the SJTMI. This was extended to SIGGRAPH 95 through the ATM link providing participants with a real-time view of the ocean floor.

University of California Film School

USC and GraphicsNet Digital Demo demonstrated remote collaboration during their HollyNet demonstration. Graphics designers at USC and the LA Convention Center collaborated on digital productions during the course of SIGGRAPH 95. This included student creation being accessed by industry professionals at the LA Convention Center.

MBONE Unplugged

The objective of the MBONE Unplugged project was to create a mobile studio for a week long KSIG-TV. SIGGRAPH 95 exhibitors, Interactive Communities, papers and panels provided the programming. The productions would be recorded for later Internet access and broadcast live during the week to the MBONE. In addition to the standard MBONE objectives, content and lab facilities for local educators to learn about the Internet were provided.

In Figure 5 Jon Bigelow from the Naval Postgraduate in Monterey California displays the portable MBONE cart used to produce KSIG-TV, a mobile studio for capturing and broadcasting SIGGRAPH 95 to the Internet. This cart supported live 2-way audio/video over the Internet. It was based on an SGI Indy, an APC uninterruptible power supply, standard VHS VCR and TV monitor, two VHS video cameras and a video switch to select camera/audio source. Two AirLAN wireless bridges were used to get from the mobile cart to the GraphicsNet for transmission. A Sun Sparcstation located in the GraphicsNet booth was used as an MBONE Router. Monitoring facilities in the SIGGRAPH 95 Online area were available for inclusion of content into the daily production features on the Web.

The Naval Postgraduate School took over the MBONE project one month before SIGGRAPH 95 started. They were responsible for content scheduling, technical details of making the MBONE work in a dynamic and noisy environment like SIGGRAPH 95 and production.

World Wide Web

The servers for the World Wide Web, including the www.siggraph.org server, were directly attached to the ATM network. Users coming in from the Internet went from the Internet router to the ATM network to retrieve the Web pages. Local access from the GraphicsNet access Kiosks went directly over ATM to the Web server. This worked flawlessly and provide a performance increase over Ethernet attached access.

GraphicsNet '95 Technical Details

The primary goal of GraphicsNet was to provide a single networking infrastructure to support a variety of user requirements. User requirements included high-speed ATM connections to support video, audio and remote collaboration. Also required were traditional Ethernet connections for Internet access, file sharing and local Web activities. The Digital Demo significantly increased network requirements due to its high-bandwidth video storage and retrieval requirements. The Digital Demo also required access to databases located throughout the LA Convention Center and throughout the LA area. VRML and HTML activities at the conference also placed a large load on the network.

It was fortunate that the GraphicsNet team had the foresight to select a scalable network architecture early in the planning phases. The number of connections and size of the network grew far beyond original expectations. It was expected that the Ethernet network would consist of no more than 20 organizations for a total of less than 40 connections. It was also expected that the ATM network would have no more than 20 computers directly attached. In the wide area ATM network it was expected that 2 organizations would connect. The HiPPI Network was expected to be 15 hosts from 5 different organizations. In reality the Ethernet grew 10 fold for a total of 400 connections from 86 different organizations, including 40 different

locations from ACM/SIGGRAPH. The ATM network tripled with participation from 15 different organizations including 25 different locations for ACM/SIGGRAPH. The HiPPI network stayed about the same size.

Network Architecture

The GraphicsNet team had a desire to create a network that was as contentionless as possible, not only in the local network but also out to the Internet. The team decided ATM was the best technology to provide an integrated network infrastructure that would be flexible enough to handle the variety of requirements while providing the best throughput all around.

Five months before the conference, the goal was set to build a network based on the new networking paradigm of switched internetworks. Switched internetworks provide dedicated bandwidth for each user on the network, much like today's telephone system. The computer opens a connection to the destination computer and starts sending data. This is in contrast to the shared networks installed over the last 10 years. Shared networks are similar to the party line telephone system of the past. The computer picks up the "phone" and listens to see if anyone is "talking." If not, it "talks" by transmitting its data onto the shared media. If someone else is talking on the network, the computer "hangs up" and waits for a period of time to try again. This is repeated until the network is available for the computer to transmit the data.

To build a switched internetwork that was flexible and scalable required ATM as the backbone. Building an ATM backbone throughout the LA Convention Center allowed any end-user node type to be plugged into the network at any point. These nodes might be computers or video cameras. It also created a low latency environment and simplified administration by removing the necessity for a large amount traditional routers.

The ATM backbone also supported a wide area ATM link to Pacific Bell's CALREN ATM network and one to Sprint national ATM network. These links supported a variety of high-speed applications based on real-time, low-latency, full motion video and graphics over the ATM data network.

The second level of the network was originally designed to be Ethernet Switches with ATM uplink cards. These devices would take in 16 Ethernet devices, each with their own dedicated 10 Mbps (Ethernet's maximum transmission speed), and connect them directly to ATM. The ATM uplink would be 155 Mbps or 15 times as fast as Ethernet. Therefore, each of the sixteen nodes attached to the Ethernet switch could communicate over the ATM backbone at over 90% of their available 10 Mbps. The only area of contention would be the 155 Mbps (SONET OC-3c) uplink to the ATM network. It was felt that having 16 users simultaneously transmit at a full 10 Mbps would be unlikely.

In addition to the ATM backbone, an ATM LAN was also necessary. A physical distinction between the ATM LAN and the ATM backbone was not made. Users were directly connected to the same ATM switches as were the Ethernet hosts. However, a logical difference was made. All of the Ethernet switches would be in a single emulated Ethernet LAN, while the ATM network would exist as a separate IP network. A LAN Access device, the LAX-20, was used to route between the two logical networks.

For some very specialized applications, a HiPPI network was also designed. This network design included several HiPPI switches and a HiPPI-to-ATM gateway. The HiPPI network was designed to be physically and logically separate from the ATM backbone and Ethernet network. A HiPPI-to-ATM gateway provided connectivity between the main conference network and the HiPPI Network.

Internet connectivity was the largest application requirement. Users wanted to access the Internet to download new software, read email, and to provide demos from their WWW servers located back at their corporate headquarters. The SIGGRAPH organization moved the www.siggraph.org machine to the LA Convention Center and made it available to the Internet from the conference network. Initially the team wanted to connect to VBNS Internet backbone at San Diego Supercomputing Center with a SONET OC-3c ATM link. San Diego wasn't ready for user connections at ATM speeds last August. Therefore, the Internet connection was made using a standard DS-3 (45 Mbps) data link through a router. This access speed was selected due to the large number of users that would directly access the World Wide Web as part of their demonstrations. It was also felt that the ATM attached hosts could potentially generate a large amount of traffic to the Internet.

This network design was very ambitious for such a small team to build in less than seven days. The sheer size of the network, 400 Ethernet connections and 100 ATM connections, was a challenge. Although the technologies being deployed were new, the team felt the products solid enough to build a production network. The overall architecture of the network was set in stone by the end of May 1995. The team started on the design and implementation.

LAN Design and Implementation

The major goal of GraphicsNet, to build a switched internetwork using ATM, was accomplished. Typical networks of this size employ a variety of routers to segment the network into small broadcast domains. This provides users with a smaller number of computers on the shared media network. The routers must then be configured to pass information between these broadcast domains. Heavy use of routing leads to bottlenecks in the routers and a complex environment to manage. Instead, the GraphicsNet team deployed routers only where they were absolutely necessary, significantly reducing complexity. This lead to a 99% uptime rating between Monday and Friday. Two fiber problems caused brief outages on the network during the week. User complaints were nonexistent. The network performance was outstanding and connectivity problems did not exist. The GraphicsNet team was able to enjoy what was built and the conference for several days due to the stability of the network. The biggest concern after the 7 day network installation was how to get it removed from the LA Convention Center in less than 5 hours.

The ATM Backbone was implemented as originally planned. The number of users per Ethernet switch port went from the original design of 1 to 10. This was done to reduce the number of cable drops and Ethernet switches required to build the network. Since this density is lower than what can be economically deployed using a router, the performance was far beyond expectations. The following sections describe the details of each of the major components of the network.

ATM Backbone

Using an ATM Backbone for the conference network simplified the network design tremendously. All data leaving a location did so as an ATM cell. Therefore, a large switched network could be built to eliminate any backbone bottlenecks by engineering a solution that would also provide for a network hierarchy where the aggregate bandwidth increased.

The ATM backbone, the LAN and the WAN were built using 13 FORE Systems ASX-200BX ATM backbone switches. The LAN switches were connected together with SONET OC-3c links (equivalent to 10,000 phone lines). Two buildings were connected using a SONET OC-12c link (equivalent to 40,000 phone lines). SONET OC-3c link provides a data link at 155 Mbps (15 times as fast as Ethernet) and the SONET OC-12c data

link provide 622 Mbps. The ASX-200BX had 2.5 Gigabits-per-second of non-blocking switching capacity. Each network module had a maximum throughput of 622 Mbps to this switching fabric. Therefore each network module could have up to 4 OC-3c ports (155 Mbps X 4 = 622 Mbps) or one OC-12c (622 Mbps) port. Each switch can handle up to 4 switch interface cards.

The ATM switches were distributed throughout the LACC with the two major concentrations being the GraphicsNet booth in the South Hall and Digital Demo in the Concourse Area of the LA Convention Center. These two major areas were interconnected with ATM over a SONET OC-12c link through a Pacific Bell Central Office (CO). This connection was required because the LA Convention Center did not have fiber between the old and new portion of the LA Convention Center. All connections from the western end of the LA Convention Center terminated in the Digital Demo room. This included the Internet Access room, GraphicsNet access kiosks in the concourse and west lobby, all Ethernet connections in these areas and the ATM attached computers in the Digital Demo.

The southern portion of the LA Convention Center had 4 secondary switching areas that tied into the main ATM switch area in the GraphicsNet booth. These were the south lobby, Parallax booth (which served as a focal point for 1/3 of the exhibit hall), LACC IDF 2.0 and the Interactive Communities switch tower. The Internet On-line area served as a secondary switching location for the western portion of the building due to the volume of connections for the Internet Access room and the SIGGRAPH On-line effort.

Silicon Graphics had a workgroup ATM network based on an ASX-200BX that tied into the backbone via an OC-12c connection back to the GraphicsNet Booth. In their private network they had a Challenge L with 2 ATM adapters, several Indys and Indigo IIs. These workstations ran a variety of applications over ATM including InPerson (software for video conferencing with multiple attendees over data networks) which had been configured to take advantage of the bandwidth required by ATM.

Ethernet over ATM

In order to provide users with a network free from bottlenecks, it was felt that the Ethernet network needed to not only be switched, but also directly connected to the ATM Backbone. This required an Ethernet switch with an ATM uplink. These devices could not be obtained for the conference. Plan B was to use Ethernet switches with FDDI ports into FORE Systems LAX-20s which would then provide the uplink to ATM. Unfortunately due to customer demand these were also not available for the conference. The final architecture was to use intelligent Hewlett Packard hubs and LANNET Ethernet switches attached to the Ethernet port on the LAX-20 which provided for the ATM uplink. Users that expressed a need for high-bandwidth connections were given a dedicated Ethernet port on the LAX-20 or put directly on ATM. Performance problems were alleviated due to the small number of users, 10 to 15, per switched Ethernet port.

In order to reduce the complexity of the network a single emulated LAN was used for Ethernet hosts. This was made possible through the capabilities of FORE Systems' ForeThought 3.0 software. From a user's perspective, all 400 hosts were on a single IP subnet. Typically a bridged network of this size would not support this many users without severe network performance degradation. The switched implementation of this network broke down the maximum number of users on one side of a "bridge" to 10. So the network looked like 50 bridges connected together with 10 or less computers per bridge. These 50 virtual bridges looked as if they were all directly connected to every other bridge on the network. That is, there was a single hop between any two bridges on the network. This was the function that the ATM network provided, a contentionless, direct connection between all of the Ethernet segments.

During the daytime hours the network averaged 45% utilization with peak utilization of 94% for periods lasting more than 30 minutes. We did not record any broadcast storms and user complaints about performance were non-existent.

ATM attached Hosts and Servers

The requirements for ATM attached hosts were much higher than expected. Initially it was thought that there would a maximum of 20 hosts on the ATM network. GraphicsNet installed 60 hosts at the LA Convention Center. Between the remote connections and other devices at the conference the total ATM devices connected to the network was 100.

Seven primary applications used ATM attached hosts:

- GraphicsNet access "kiosks" and servers
- The Internet On-line Area
- VRML and Video Servers
- Digital Demo
- Telemedicine Demonstration
- MAGIC Gigabit Test Bed
- Monterey Bay Educators

Each of these applications along with their network impact will be covered in more detail in the application section.

HiPPI Network

Several exhibitors performed demonstrations over the HiPPI Network. The GraphicsNet'95 team deployed three HiPPI Switches from Essential Communications using serial HiPPI. The original HiPPI specifications call for a set of 100 pair copper cables. The distance limitation for these is 50 m. Serial HiPPI is based on a pair of fiber optic cables that can transmit the data up to 10 km. The HiPPI switches from Essential Communications used network modules that allow for the fiber to be directly connected to the switch, eliminating the requirement for an additional converter box.

Routing between Local Networks and to the Internet

The Ethernet network was an emulated LAN over ATM. Servers for the Web and the Internet room X-terminals were directly attached to the ATM network, therefore the Ethernet hosts needed a high speed link to the ATM network. The ATM network also needed a link to the Internet. It was important that the ATM attached hosts did not have to go through the Ethernet network before being sent out to the Internet. Therefore a two-node FDDI ring was deployed. The three devices on the ring were an LAX-20 routing between the ATM network, the emulated Ethernet and the FDDI ring. The second device was a Cisco 7000 Router which provided the routing to the Internet. In this configuration both ATM and Ethernet attached hosts had a single hop to the Internet. It was also a single hop from any Ethernet attached host and its ATM server.

The HiPPI-to-ATM gateway, Nethiway (provided by Essential Communications), filled the need for routing between the HiPPI network and ATM. Several servers on ATM had file systems stored on HiPPI Raid devices like Maximum Strategy's proFILE NFS Server.

ATM and HiPPI attached Disk Arrays

Maximum Strategy provided ATM and HiPPI attached disk arrays. These disk arrays offered large amounts of disk storage at very high data rates. By attaching the disk systems to high speed networks, the bottleneck of getting the data to the user was removed. Although the technology was delivered at SIGGRAPH 95 and available on the network, very few users took advantage of it. This is an area that the SIGGRAPH 96 networking team can exploit.

Metropolitan and Wide Area Links

SONET Installations into LACC

One of the first hurdles the GraphicsNet team ran into was the lack of a fiber infrastructure in the LACC. The LACC did not have any fiber available for customer use before SIGGRAPH 95. Several quotes came in to link up the LA Convention Center and were dismissed due to cost. The best way to get between the two major halls was through Pacific Bell point-of-presence (POP) in each hall. Since Hall K had been built recently it did not have a PacBell POP. After some negotiation with PacBell and the LACC Pacific Bell started a full blown SONET OC-48 installation into the LACC. They created a three node OC-48 ring that ties together the west hall, south hall and the PacBell. This provided the LA Convention Center with the capabilities to meet the service requirements of any exhibitors for the extended future.

SIGGRAPH 95 used these services for GraphicsNet. Three DS-3 circuits were provisioned into the south hall; one for the CAL-REN ATM link, the second for the Sprint ATM Link and the third for the DS-3 to the Internet. The two ATM DS-3s were plugged directly into an ASX-200 switch borrowed from HP Labs for GraphicsNet. The DS-3 to the Internet was attached to a Digital Link CSU/DSU which was attached to the Cisco Router. The router and CSU/DSU were donated by HP Labs. Additionally, GraphicsNet provided an OC-12c link between the west and south halls. This was directly attached to an OC-12c ATM network module in ASX-200BX switches on the respective ends.

The installation by PacBell was completed just over a week before the conference started. GraphicsNet attached to the services starting on the Friday before the conferences. The links between the LA Convention Center and Pacific Bell were extremely clean, however circuits in other portions of the network were not. Therefore, the OC-12c link came up and stayed up for the entire conference. It took until late Monday afternoon to debug all of the problems with the DS-3 links. That afternoon both the ATM connections and the Internet connection became active. The local network at the LA Convention Center had been up since Saturday. At that time the Internet connection had become active. It went down due to a problem in the long distance carrier's corporate office. Once this was located and repaired, the connection came up and performed flawlessly.

Funding for the SONET OC-48 ring came from Pacific Bell and the LA Convention Center. Although the LA Convention Center did not have to pay for the half million dollar installation, they were required to pay for some of the fiber installation within the LA Convention Center. Pico Boulevard was torn up to run fiber into the LA Convention Center from PacBell's fiber runs outside of the building.

Permanent Fiber Installation

Most of the fiber installed in the LA Convention Center for SIGGRAPH 95 was removed during the tear down process. Two fiber runs were designed and left permanently in the LA Convention Center. These runs required the installation of a large amount of conduit to get between floors and through fire walls. The LA Convention Center had to make sure that the installation would met the fire codes for LA. The GraphicsNet Team designed a permanent fiber installation that went from the PacBell POP under the West Hall into the LACC IDF on the same level and then a second run from that IDF up to the second floor IDF. Six strands of single-mode and six strands of multi-mode fiber was installed. This provided the connectivity from the main portion of the building to the POP under the West Hall where PacBell's facilities terminated. GraphicsNet used this fiber to run the OC-12c link, for several OC-3c links and to extend Ethernet links beyond their maximum 100 meter lengths for hard to reach portions of the LA Convention Center like Petree Hall.

Conclusions

The conference network at SIGGRAPH 95 was a success indicated by the high reliability and availability during the conference. The number of users that wanted a connection to the conference network, to do live demonstrations using the Internet, accelerated as the conference date came closer. Several companies asked for network connections the week before the conference.

Another factor in the success was that users of the network gained experience and knowledge in what it takes to run their applications over high-speed networks like ATM. The telemedicine group learned about sending their video over a data network that spaned the continent. They also learned how to deal with and what to expect from a national ATM network. The WebForce engineers from SGI observed both novice and experienced Internet users using their VRML application in high-speed network environment. They were able to offer advanced technology because of the ATM infrastructure and found ways to improve the user interface.

Acknowledgments

Over 150 people where involved in some aspect of GraphicsNet at SIGGRAPH 95. I will mention the key contributors and team leaders here and rely on the GraphicsNet'95 Web pages to serve as a more complete acknowledgment.

Without the sacrifices made by the GraphicsNet team, the network would not have come to fruition. This team of networking engineers built a network based on very aggressive goals and did so in one week: Jeanette Dravk, Steve Johnson, Craig Schell and Amy Wong of FORE Systems, Inc. Peter Haddad and Randy Strickfaden of HP Labs. Keith Neeson and his team from Pacific Bell. Wesley Hein and Rick Harriot of Visual f/x and their team. John Thuette of Essential Communications. Barry Willis of Eastern Carolina University. Diana Starr of Silicon Graphics. Don Brutzman and Jon Bigelow of the Naval Postgraduate School. Kevin Harrington, Renee Manning, Michelle Markey, Alan Martin and Bob Young of FORE Systems also provided help.

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Glossary

ATM
A transfer mode in which data is transmitted in the form of 53 byte units called cells. Each cell consists of a 5 byte header and a 48 byte payload. ATM is specifically designed to provide a common networking infrastructure for voice, video, and data networking applications. ATM is the new networking paradigm which switched internetworks are being based on.

Avatar
A graphical representation of another "being" in a virtual world. The other being is most likely going to be another user who has entered the virtual world through a remote computer.

DS-3
A wide area link through a local and/or long distance carrier that runs at 45 megabits per second. This is 4.5 times faster than a single Ethernet connection. This connection is often called a T-3 or DS-3. The only difference between a T-3 and a DS-3 is that AT&T holds a trademark on T-3.

Emulated LAN:
An emulation of a physical medium (Ethernet or Token Ring) over an ATM network. Typically an emulated LAN used LAN Emulation.

LAN Emulation:
LAN Emulation emulates a physical medium (Ethernet or Token Ring) over ATM to allow hosts to communication over ATM without changing the upper layer networking protocols. LAN Emulation works at the MAC Layer, therefore none of the endstation drivers or hardware need to be changed.

MBONE
The MBONE is a virtual network providing audio and video broadcasts over the Internet. Video is digitized with a workstation and it is then multicast to the Internet. Anyone with the appropriate Internet connection and software can receive the audio/video broadcasts.

OC-3c
This is an ATM connection of 155 megabits per second, 15 times faster than Ethernet.

OC-12c
This is an ATM connection of 622 megabits per second, 62 times faster than Ethernet.

SONET (Synchronous Optical Network)
An international standard defining the mechanism for transmitting digital information over fiber optic lines.

Switched Internetwork
A switched internetwork differs from today's local area networks in that it provides each user with a full 10 Mbps (Ethernet) connection to the rest of the network. A switched connection does not have to share bandwidth with other stations as in today's hub based networks. Shared networks can be compared to the party-line phone system of the past. Switched networks are like the current phone system in that when you pick up the phone you know you don't have to wait for someone else to stop talking on your local line.

Virtual Channel Connection
An abstraction in ATM to describe a communications connection that is not tied to a physical link. A single fiber can have multiple virtual channel connections on them, all going to different destinations.

Virtual Path
An abstraction in ATM to describe a communications connection that is not tied to a physical link and is made up of many virtual channel connections.

VRML
VRML stands for Virtual Reality Modeling Language. VRML is a draft specification for adding 3D data to the Web.